Belt. Glacial Period

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AN EXAMINATION OF THE THEORIES THAT HAVE BEEN PROPOSED TO ACCOUNT FOR THE CLIMATE OF THE GLACIAL PERIOD.

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In the speculations I ventured to make in a recent work* on some of the phenomena of the Glacial period, I purposely avoided entering on the question of the cause of the great accretion of ice, believing that the time was not ripe for its discussion, and hoping that it might be taken up by some astronomer, as it is to Astronomy rather than Geology that we must look for a solution of the problem. I find, however, that my explanation of the facts of the "great ice age" are constantly met by objections founded on the theories of the cause of that event; and I propose in the present paper to discuss the principal hypotheses that have been advanced to account for the origin of the Glacial period, and to endeavour to show that my speculations on the extent and effects of the ice are in accordance with, and a necessary consequence of, the theory that is most in harmony with the facts with which we have to deal.

1. *Theory of a Change in the Relative Position of the Continents and the Ocean.*—In that great work the "Principles of Geology," in which the foundations of the modern science were laid in 1830 by Lyell, and in successive editions in which the veteran philosopher has ever kept abreast of advancing knowledge, he has brought forward and supported the theory that great oscillations of temperature have been produced by changes in the relative positions of land and water. This theory he has enforced with a wealth of illustration derived from his vast acquaintance with geological and geographical facts, and by the masterly arguments of a clear, comprehensive, and judicial mind. Chiefly through

* The Naturalist in Nicaragua, p. 262.

his powerful advocacy, after nearly half a century has elapsed, it still holds its ground among the rival views that have been advanced, and deserves our first consideration.

Lyell takes for his starting-point the undoubted fact that the sea and the land are now in some parts changing places. Along some coast lines the land is either slowly sinking or has sunk in post-glacial times, whilst in others the continents have been raised above their former level. He proceeds to show that the climate of a place is greatly dependent upon its position with respect to great masses of land or water; that an insular climate is less extreme than that of the interior of a great continent; and that currents of water from the tropics, or from the arctic regions, are very effectual in raising or lowering the mean temperature above or below what is due to distance from the equator alone. He then considers what change in the relative position of land and water would produce the warmest and what the coldest climate, and comes to the conclusion that if all the land was distributed around the equator we should have the warmest climate possible due to geographical conditions, and that if all the land was situated at and around the poles we should have the extreme of cold.

There can be little doubt that if the second set of conditions prevailed, or even some approach to them, they would be effectual in rendering more severe the climate of polar regions, and in causing a greater accretion of ice than now prevails. A rise of polar and a submergence of tropical lands would certainly lower the temperature of the arctic regions. A mere rise of land, sufficient to close Behring's Straits and to connect America through Newfoundland with Europe, would, by shutting off all warm currents from the polar seas, tend to a greater accumulation of ice, as the heat of the Gulf Stream and other warm currents—that is now expended in tempering arctic seasons and melting polar ice—would then cause greater evaporation, and consequently greater precipitation, on the frozen lands of the north. But it must not be forgotten that the warm currents flowing northwards are counterbalanced by cold ones flowing southwards; and if, on the one hand, regions enjoying a warmer climate through the influence of the Gulf Stream would then be shut off from its influence and subjected to greater cold, so, on the other, coasts—such as that of eastern North America—now cooled by polar currents, would be laved by warmer waters. Yet it is on the eastern side of North

America that the ice extended farthest towards the equator in the Glacial period.

When Lyell first propounded his theory geologists were very imperfectly acquainted with the facts that were to be explained, and it was thought that if it could be shown that by an alteration in the configuration and distribution of land, and a change in the direction of the currents of the ocean, icebergs might be floated down to the latitude of London, lowering the temperature as they do now in South Georgia in lat. 54° S., so as to allow of a perpetual covering of snow and the existence of glaciers on the higher grounds, a satisfactory solution of the problem would be arrived at. But in the half century that has nearly passed since then our conceptions of the extent of the ice of the Glacial period have slowly but greatly expanded, and we know now—although many English geologists still close their eyes to the evidence—that the problem to be solved is not one of icebergs floating over submerged lands, but a vast piling up of ice and snow around the poles, that accumulated until it flowed outwards over the existing continents. Let us trace this great ice-sheet round the northern hemisphere, as we are now nearly enabled to do by the latest observations on its extent in northern Asia.

Commencing in North America, we learn from Dana and other eminent American geologists that to the north of the St. Lawrence the ice was at least 12,000 feet, or $2\frac{1}{2}$ miles, in thickness; in the northern parts of New England was over 6000 feet in thickness, and, gradually thinning southwards, reached in the lower grounds the parallel of 39° N. in the southern parts of Pennsylvania, Ohio, Indiana, Illinois, and Iowa, whilst along the mountain ranges local glacier systems reached in the tropics at least as far as Nicaragua, where within 13 degrees from the equator I found undoubted traces of glacier action reaching to 2000 feet above the sea-level, where snow now never falls.

Coming eastward we find, in Nova Scotia and Newfoundland, everywhere evidence that they were completely overwhelmed with ice. Iceland, according to Robert Chambers, is scored across from one side to the other, and was buried in ice that may have reached the British Isles, for the Hebrides and the north-eastern extremity of Scotland were overflowed by ice that came from that direction. This ice, overflowing Caithness, joined by great streams from Scandinavia, and further reinforced by glaciers from the mountains of Scotland and the north of England, pushed down the bed of the German Ocean, reached as far as the coasts of

Norfolk, and thrust up great masses of chalk and other angular rocks upon the land. We have a measure of its thickness in Southern Yorkshire, and learn that it was not so deep on the eastern as it was on the western side of England, for the drift does not reach higher than 600 feet above the sea, excepting where the Wye, the Calder, and the Aire cut through the Pennine Chain, and form passes through which the ice streamed from the west, where it was much higher. The Irish Sea was filled with it, flowing southwards, at least 2000 feet thick. It butted against the Welsh mountains, and, dividing, one part pushed up the valleys of the Mersey and the Dee, and through what has been called the Straits of Malvern, certainly as far as the water-shed of the Severn, probably as far as the Bristo Channel; the other and larger stream, shouldering the western slopes of the mountains of Cardiganshire, flowed across Anglesea to the Atlantic. In Ireland the ice was still thicker, and Mr. Campbell considers that in the extreme south of that island he has obtained proofs of it having been at least 2000 feet thick. This thickening of the ice westward proves that the British Isles were not glaciated from Scandinavia.

Passing across to the continent we find Scandinavia hugely glaciated, and that the ice-sheet that flowed from it filled the Gulf of Bothnia and the Baltic. Denmark was assailed by the advancing ice, and everywhere traces are left of its vast extent and force. In the Island of Möen the chalk strata are dislocated and folded together, inclosing in their folds patches and seams of boulder clay. The Danish geologists have ascribed these to a faulting and bending of the strata since the Glacial period; but both in Nova Scotia and at Abergairn, in Aberdeenshire, I have seen great masses of strata that have been pushed along horizontally over others by the great force of the advancing ice, and think that the post-tertiary contortions of the strata in Möen must be due to the same agency. After crossing the Baltic the ice crept southwards, and all over Northern Germany and Holland blocks of stone strew the surface that have been brought by it from the mountains of Norway and Sweden. It reached its southern limit somewhere about Antwerp, and eastward the range of the northern drift has been traced to an irregular line across the Continent. In European Russia the ice reached to Nijni Novgorod, in lat. 52°; to which parallel I have also traced it in north-western Asia, near Pavlodar, in Siberia, and in a paper read before the Geological Society of London have described the facts that have

led me to the conclusion that the ice from the north blocked up the whole water-shed of Siberia as far as the borders of Kamtchatka.

We thus find everywhere in the northern hemisphere that the ice thickened northwards, that it radiated from the pole; and that its margin nearly girdled the world, and probably would be found to have done so completely if there were land to preserve its traces.

There are many geologists who believe that these northern lands were not all glaciated at the same time,—that, for instance, the Glacial period of North America was not contemporaneous with that of Europe. Those who thus argue adopt, in some form or other, Lyell's theory that the cold of the Glacial period was produced by a change in the distribution of land and water. Thus Mr. Hopkins, in 1852, calculated that if—by some change in the relative position of sea and land—the Gulf Stream could be diverted from its present northerly course, whilst northern and western Europe were submerged to the extent of 500 feet, and subjected to the influence of a cold current passing over the depressed area, the snow-line would descend to 1000 feet above the sea-level in Wales and the West of Ireland, and glaciers would reach the sea. Although this amount of change would be totally insufficient to account for the facts of the Glacial period, it may still be useful to point out that not a single scrap of evidence has been adduced to show that the Gulf Stream ever passed over any portion of Europe or America that is now dry land.

Throughout the whole of the Tertiary period the continents appear to have had much the same area and figure as they at present possess. Dana has also pointed out that, even so far back as the Jurassic period, the Gulf Stream exerted the same kind of influence upon the temperature of the North Atlantic as it does now. He considers that the existence of corals in the English oolites proves that the coral reef boundary extended 22 degrees of latitude beyond its present farthest northern point, and believes that the Gulf Stream must have aided in this result. Other facts indicate its existence and influence in cretaceous and tertiary times,—as, for instance, the representatives of the French Faluns on James's River, in North America, denote a cooler climate in lat. 37° N. than prevailed at the same time in lat. 47° N. in Western Europe,—whilst in the glacial epoch the extent of the ice in Western Europe and Eastern North America curiously and suggestively conforms with the curve of the present isothermal lines due to its action. Just as

now, the isotherm of 50° F., passing across the south of England near the latitude of London and the Bristol Channel, sweeps south-westwardly across the Atlantic, and reaches to about Baltimore, in North America, so in the Glacial period the margin of the ice, flowing southwards, attained nearly the same limits; indicating that the warm waters from the tropics then, as now, were deflected against the western coasts of Europe by the rotation of the earth, and gave them a higher temperature than the same latitudes on the eastern coasts of America. The sea teems with life, and it is not possible that this current could have flowed over any part of Europe without leaving many memorials of its course behind it. But even if it had been diverted, and a cold current brought icebergs from the Arctic regions past the British Isles, how could that, or any modification of such a theory, cause continental ice to reach the sea-level in lat. 39° in North America? I cannot imagine any alteration of the present coast-lines that could cause a greater curve in the isothermal lines than at present exists in the North Atlantic; and to assume that during the Glacial period the warm and cold currents shifted their position all round the hemisphere, so as to bring every part, at one time or other, within a greater extreme of cold than now anywhere prevails, is to call for an amount of movement in the earth's crust that no evidence warrants nor analogy suggests.

Whilst Lyell, in his latest works,* adheres to his opinion that former changes of climate have been chiefly governed by geographical conditions, he candidly admits that since he first attempted to solve the problem, our knowledge of the subject has vastly increased, and that it has assumed a somewhat new aspect, so that he now considers it probable that astronomical causes may have combined with geographical changes to produce an exaggeration of cold in both hemispheres. The principal of these astronomical theories I shall now take into consideration, but I shall have in the sequel—when I come to show what bearing the facts of the Early Tertiary period have on the discussion—to make some further remarks upon the insufficiency of geographical changes to account for the great oscillations of temperature of which we have geological proofs.

2. *Theory of an Increase of the Ellipticity of the Earth's Orbit.*—Mr. Croll, in a series of papers published in the "Philosophical Magazine," has advocated, with great ability

* Principles of Geology, 1872, pp. 173 and 284.

and learning, and strengthened by laborious calculations, the theory that the cold of the Glacial period and the warmth of other geological epochs were due to great changes in the ellipticity of the earth's orbit. As has long been known, the earth, in its annual course around the sun does not describe a circle, but an ellipse, and is much nearer to the great luminary in some parts of its course than in others. Astronomers have also proved that the eccentricity of the orbit varies during vast periods of time, and that at its greatest eccentricity—one of which periods happened about 200,000 years ago — the earth in aphelion was nearly 98,500,000 miles distant, whilst now when in aphelion it is about 90,000,000 miles from the sun.

One result of the eccentricity of the orbit, combined with the obliquity of the ecliptic, or the angle that the axis of the earth makes with the plane of its orbit, is, that at present the sun is north of the equator about $7\frac{1}{2}$ days longer than it is south of it. But as at the time the sun is south of the equator the earth is nearest the source of heat, the southern hemisphere receives just as much heat in its shorter summer solstice as the northern hemisphere does in its longer one. Astronomers have calculated the effect of a much greater eccentricity of the orbit, and have unanimously come to the conclusion that the absolute amount of heat received by the two hemispheres would be the same, however great that eccentricity might be. But as the total amount of heat received from the sun is inversely proportional to the shortest diameter of its orbit, it follows that during the periods of greatest eccentricity the absolute amount of heat received by the earth, and distributed equally to the two hemispheres, would be slightly in excess of that received when the eccentricity was much less.

The general conclusion arrived at by astronomers before Mr. Croll examined the problem—including the eminent names of Humboldt, Arago, and Poisson—was that the climate of our globe could not be affected by any possible change in the ellipticity of its orbit. In this opinion Herschel—who at one time thought that great changes of climate might be so produced—appears afterwards to have coincided. Mr. Croll, however, states that in arriving at this conclusion a most important element of the enquiry had been omitted. Fully admitting that the absolute amount of heat received in the two hemispheres would be the same, however great the ellipticity might be, he yet urges that in that hemisphere in which the nights were longest there would be most heat lost by radiation, and

in that way the mean temperature would be greatly lowered.

Mr. Croll puts his theory briefly in these words :—" The southern hemisphere is further from the sun during its winter than the northern, and therefore cools more rapidly. It is, however, nearer to the sun during its summer than the northern, and on this account cools more slowly. The heat thus saved during summer would exactly compensate for that lost during winter were the two periods of equal length ; but as the southern winter is longer than the southern summer by more than $7\frac{1}{2}$ days, there is on the whole a greater amount of heat lost during winter than is saved during summer." " The greater length of the winter half year over the summer half, when the eccentricity is near its maximum, would affect the climate in two different ways :— (1), by allowing the ground to cool by radiation to a greater extent than it would otherwise do were the (summer) seasons of greater length ; and (2), by lengthening the ice-accumulating period and shortening the ice-melting period. The influence of the first cause upon the glaciation of the country would probably be felt to a considerable extent ; but it is to the second that we must attribute the principal effect."* The above was written in 1865, but I cannot find that Mr. Croll has modified his theory in any later writings ; and Mr. James Geikie, his colleague on the Geological Survey of Scotland, has, during the present year, in his work " The Great Ice Age," adopted it, and in discussing it has described it substantially as above. Now if it be true that the hemisphere, that has its winter when the earth is farthest from the sun, will have its mean temperature reduced by an excess of radiation, whilst that of the opposite hemisphere will be correspondingly increased, we have certainly a true cause of former great oscillations of climate. Before, therefore, entering on the consideration of some other causes that would, according to Mr. Croll, be brought into action and intensify the effects, it will be well to examine the fundamental basis of the theory.

1st. Would there be more radiation of heat into space, and consequently increased cold, at times of the greatest ellipticity of the orbit in that hemisphere whose winter happened when the earth was furthest from the sun ? Mr. Croll, as we have seen, answers in the affirmative, and in the shape in which he puts it it appears as if it would be so. As at that time the number of hours of night in each

* Reader, 1865, p. 631.

year were much more in one hemisphere than the other, it is quite certain that more heat would be radiated during the nights that were longest. But, and this is the fallacy on which it seems to me Mr. Croll's argument rests, the earth radiates heat in the day time as well as at night, and this has not been taken into consideration. The warmth of the day depends on the excess of heat received over what is radiated, not that there is no radiation at that time; and if we take into account the heat radiated during the day we shall find that no more is lost in one hemisphere than the other from that cause. And if the absolute amount of heat received from the sun be equal whatever the amount of ellipticity, and the absolute amount of loss by radiation also equal when we calculate that radiated during the day as well as that during the night, it is evident that the absolute difference between the heat received and the heat lost, or the mean temperature of the two hemispheres due to these causes alone, must be the same whatever the amount of ellipticity of the orbit may be.

2nd. Would the lengthening of the ice-accumulating period and the shortening of the ice-melting period cause a greater accretion of ice? Here again Mr. Croll and his followers answer unhesitatingly in the affirmative, and they put it in this way:—"At the time of greatest eccentricity during the long winter of aphelion, longer by thirty-six days than the summer of perihelion, such an accumulation of snow and ice would have taken place that even the diminished distance between the earth and the sun in summer time would be powerless to effect its removal."* Here, again, I think the argument is based on a misconception. It is not a fact that our winter begins as soon as the sun has passed the autumnal equinox, though what is called the winter solstice does. The nights are longer than the days, but snow does not immediately begin to fall nor water to freeze, and our winter does not commence on the 22nd of September, but several weeks later. In the shorter but hotter summer of perihelion some excess of heat must be stored up in the earth, the sea, and the atmosphere, not to be entirely given up until long after the winter solstice has been entered on. The advocates of this theory affirm that the mean temperature would be lowered because the heat of the short summer would be taken up in melting the ice that had accumulated in winter, but a pound of water in passing from a liquid to a solid state

* The Great Ice Age. By James Geikie. 1874. P. 139.

evolves just as much heat as is required to melt it again, and the heat given off in winter by the freezing water is equal to that absorbed when it melts again, so that the mean temperature is not affected.

Again, it is said that clouds would accumulate around the pole with its winter in aphelion. Why they should do so does not appear very clearly, but clouds would receive the rays of the sun on their upper surface, and in some way or other the heat would be utilised in ameliorating the climate; nor should it be forgotten that clouds prevent radiation during the night as well as intercept the sun's rays during the day.

There is, however, a cause not touched upon by Mr. Croll that does act in preventing the excess of heat of summer counterbalancing its diminution in winter where snow covers the ground. It is not because the heat is used up in melting the snow, but because much of it is not so used up but is reflected back into space from the white surface. If it were not for this, snow would nowhere be perennial, but everywhere the heat of summer would dissolve the snows of winter; and if, without taking into account any lengthening of the winter by reason of the ellipticity of the orbit, the whole of the winter solstice were an ice-accumulating period, it would now gather year by year until it overwhelmed the temperate zones, because the six months' snow would reflect so much of the other six months' heat that it would not be melted but would gradually accumulate. It does not do so, because only at the very poles are there six months winter and six months summer, and the ice-accumulating period gradually decreases when we leave the poles, and reaches zero long before we arrive at the tropics. These conditions were probably the same at the time of greatest ellipticity, and at the most only a very small amount of heat could be lost by reflection from snow-covered lands more than now: and as at that time—according to the law that the amount of heat received is in inverse proportion to the length of the shortest diameter of the orbit—there would be a slight increase in the absolute amount of heat received from the sun, it is probable that one would counterbalance the other; and I cannot but come to the conclusion that Arago was right when he affirmed that even if the ellipticity of the orbit was much greater than astronomers have shown to be possible, "still this would not alter in any appreciable manner the mean thermometrical state of the globe."

Mr. Croll has sought to strengthen his theory by

endeavouring to show that other physical causes would be brought into operation during a great ellipticity of the orbit which would tend to decrease the temperature of the hemisphere that had its winter in aphelion, and to increase that of the other. The most powerful of these he considers would be a change in the great currents of the ocean by which at present a large amount of heat is conveyed from the tropics to the poles. He maintains that these currents are produced by the trade-winds, and that when the temperature of one hemisphere was reduced and the other increased in the manner and by the causes already discussed, the trade-winds on one side of the equator would be weakened and on the other strengthened, and in consequence the warm currents flowing towards the poles would in one hemisphere be augmented and in the other decreased, if not stopped altogether. For instance, he considers that the Gulf Stream is produced by the action of the trade-winds, and that in case of a great ellipticity of the orbit when the winter of the northern hemisphere happened in aphelion the air would be chilled, whilst that of the southern hemisphere would be warmed, and thus the aërial currents flowing from the poles towards the equator would be altered. Under these circumstances "the winds from the severe wintry north would sweep with much more vigour towards the equator than the opposite winds from the south pole. And hence Mr. Croll contends that with weaker winds blowing from the south the great antarctic drift-currents would be reduced in volume, while the subsidiary currents to which they give rise, namely, the broad equatorial and the Gulf Stream, would likewise lose in volume and force. And to such an extent would this be the case that, supposing the outline of the continents to remain unchanged, not only would the Brazilian branch of the equatorial current go on at the expense of the Gulf Stream, but the Gulf Stream he thinks would eventually be stopped, and the whole vast body of warm water that now flows north be entirely deflected into the southern ocean."* Well may Mr. Geikie say that the effect of the withdrawal from the north of all these great ocean rivers of heated water would be something enormous.

But is Mr. Croll's theory of the origin of the Gulf Stream correct? Is it possible to believe that the great body of water in the Atlantic Basin would be warmed at one end and cooled at the other without some system of circulation

* The Great Ice Age, p. 142.

being set up? If currents in the air are caused by the unequal heating of different portions of it, why should not currents in the ocean be in like manner set in motion? Mr. Carpenter contends, and has illustrated by experiment, that they are; and if he be correct, instead of the Gulf Stream being lessened by the increase of ice in the north, it would be greatly augmented; and I have already shown that there is evidence of its existence and influence in the Glacial period.

Another cause that Mr. Croll thinks might be a means of increasing the vicissitudes of temperature produced by the eccentricity of the orbit, is a change in the obliquity of the ecliptic. Accepting the conclusions of some eminent astronomers that the obliquity of the ecliptic can only vary to a small extent, he yet considers that this small amount would cause a great change of temperature; that when the obliquity was at its maximum, or, according to Laplace, 24° 50′ 34″, there would be an increase of temperature at the poles equal to 14° or 15° if they were not covered with ice, but if they were, then the total quantity of ice melted at the poles would be one-eighteenth more than at the present.* On the contrary, when the obliquity was at its minimum, there would be a decrease of temperature at the poles and an increase of the ice covering them. This struck me when I first read it as a most extraordinary conclusion, and I considered it must have been the result of an inadvertence, as it appeared obvious that the effect would be just the reverse of that stated. But I find that Mr. Geikie, in his recent work, follows Mr. Croll in this as in other matters, and states that "if the obliquity of the ecliptic reached a minimum during our glacial epoch, as indeed it must have done more than once, the effect of the great eccentricity and diminished obliquity combined would be to intensify the glaciation of our hemisphere."†

As, in the former argument, I have had occasion to show that the radiation of heat by the earth during the day had been neglected, so in this calculation the all-important fact has been overlooked that, if the obliquity of the ecliptic be increased, the arctic circle will be enlarged and a greater area of the earth's surface brought within the influence of the long arctic night. A diminished obliquity, on the contrary, would lessen the difference in the temperate zones between the length of the night and day, and in so far moderate the extremes of cold and heat in winter and

* Philosophical Magazine, vol. xxxiii., p. 436.
† Great Ice Age, p. 147.

summer. The fallacy of the argument can, however, be best shown by considering what would be the effect of diminishing the obliquity to zero. When the direction of the axis of rotation of the earth became perpendicular to the plane of its orbit, the difference of the seasons of the year would disappear, and perpetual spring would reign in the arctic regions. All over the globe there would be twelve hours night and twelve hours day, and no amount of ellipticity of the orbit could have any effect in lengthening the nights and days. Every step in the diminution of the obliquity of the ecliptic would be an approach towards this state of perpetual equinox, and tend more or less to equalise the seasons. The theory of Mr. Croll is based on an assumed exaggeration, by increased eccentricity of the orbit, of the effects of the present obliquity of the ecliptic, and it is startling to find it urged that a decrease in that obliquity would increase the results.

Having thus shown that the foundations of the theory present many points of weakness, I shall next take into consideration the question of how far it is in harmony with the geological facts sought to be explained by it. One of the points insisted upon by Mr. Croll, and which is stated to be in accordance with the facts known to geologists, is that during the greatest eccentricity of the orbit periods of glaciation would alternate with others of great warmth. Whilst one hemisphere was undergoing the extreme rigour of a glacial period, the other would rejoice in a "perpetual summer." And, owing to the precession of the equinoxes by which there is a complete revolution of the equinoctial point in 21,000 years, in half that time the hemisphere that had its winter in aphelion would slowly change until it had it in perihelion. The ice that had been heaped up at one pole would melt away and be piled up at the other. And as the last greatest period of ellipticity occupied, according to Mr. Croll's laborious calculations, about 160,000 years, there would during that time be several complete revolutions of the precession of the equinoxes, so that each hemisphere would have alternately several glacial periods and several warm periods.

To prevent misconception I shall give Mr. Croll's opinion on this question in his own words. He says:—"It is physically impossible that we can have a cold and arctic condition of climate on the one hemisphere, resulting from a great increase of eccentricity, without at the same time having a warm, equable, if not an almost tropical, condition of climate prevailing on the other hemisphere." "If the

Post Pliocene period afforded no geological evidence of a warmer condition of climate in Europe than now prevails, it would be so far a presumptive evidence against the assumption that the Glacial epoch resulted from cosmical causes." "If it should actually turn out that there is no such thing as a warm and equable condition of climate somewhere about the time of an ice period, then the whole theory would have to be given up, because a warm period according to theory is just as necessary a result of an increase of eccentricity as a cold period."*

Now not only would the periods of great cold alternate in each hemisphere with periods of "perpetual summer," according to this theory, but as the ellipticity of the orbit approached its greatest eccentricity, warm or genial climates would alternate with colder ones, the extremes becoming more and more marked as the time of greatest eccentricity was neared. We ought therefore to find before the Glacial period evidence of great changes of climate, alternations of warm and cold periods, in the successive faunas, of which we have the records preserved in the Tertiary rocks. Instead of this, there are proofs of the gradual and continual decrease of temperature in Europe from the earliest Tertiary times. According to Lyell, "as we ascend in the series, the shells of the successive groups of strata—provincially called 'crag' in Norfolk and Suffolk—are seen to consist less and less of southern species, whilst the number of northern forms is always augmenting, until in the uppermost or newer groups, in which almost all the shells are of living species, the fauna is very arctic in character, and that even in the 52nd and 54th degrees of north latitude."† And if we go back to earlier Tertiary times than the Crag period, we find all the faunas—back to the very commencement of the Tertiary formations—evidencing warmer and warmer climatic conditions as we recede from the Glacial period. Nor is this evidence confined to the faunas; it is perhaps even better illustrated if we trace the successive floras from the Eocene upwards to the Glacial period. Commencing with the Lower Eocene we find in the London clay the fruits of numerous palms, belonging to genera only now found in the tropics, accompanied by the custard apple, gourds, and melons. These are followed in time by the Bournemouth beds, with subtropical Proteaceæ, numerous fig-trees, the cinnamon, and many other plants and trees, reminding the botanist of parts of

* Philosophical Magazine, vol. xxxvi., p. 380.
† Principles of Geology, p. 199.

India and Australia. In the Lower Miocene beds of Switzerland, the flora of which has been wonderfully preserved on the northern borders of the Lake of Geneva, there are still species of fig, cinnamon, palm-trees, and other subtropical vegetation, but with them appear species of poplar, hornbeam, oak, elm, and other trees now characteristic of temperate climes, which are absent from the European Eocene strata, and which indicate a less tropical climate. These beds are succeeded by the Upper Miocene strata of Œningen, still containing many exotic genera, but with a still larger proportion of species that betoken that the climate—though still more equable and warm than at present—was gradually becoming unsuitable for subtropical plants. Coming still higher in the Tertiary series, we find in the Lower Pliocene of Italy that most of the subtropical genera have disappeared, and when we reach the Newer Pliocene deposits the trees and shrubs are those now characteristic of European forests, and suggest that the climate was similar to that at present enjoyed in Europe. Then in England we find the Newer Pliocene beds, with their trees and plants of recent species, as in the Cromer Forest bed, followed by lignite beds at Bure and Westleton, containing *Salix polaris*, now only known within the arctic circle, and *Hynum turgescens*, an arctic moss. M. Nathorst, a Swedish geologist, who has studied these beds, considers that there is a gradual passage from the mild period of the forest bed, probably only a little colder than at present, to severe arctic conditions. These Bure and Westleton beds are succeeded by the till and boulder clay of the Glacial period.

If instead of the successive floras we follow the successive faunas, the land animals or the marine, we have a precisely similar succession of events, a gradual transition from the tropical forms of the Eocene and the subtropical ones of the Miocene through the more temperate species of the Pliocene, up to the arctic shells and mammals that usher in the Glacial epoch. The evidence is complete that points to the gradual cooling of the climate, and there is none whatever to show that there were any alternations of cold and warm periods. It is exactly the same kind of evidence as we should have if we travelled from the tropics along the coast of the continent of America northwards. The plants and land animals on the one hand, the inhabitants of the deep on the other, would gradually change their character; tropical forms would give place to subtropical, these to temperate, and finally, when the far north was reached, arctic species would predominate.

Mr. Croll has pointed out that though we have no evidence to support his theory in the successive faunas and floras of the Tertiary strata, yet in the Eocene beds of Switzerland and the Miocene of the North of Italy there are conglomerates containing large transported blocks of stone. Fully admitting that these were most likely transported by ice, I need scarcely remind geologists that no marine remains have been found with them, and that they were probably deposited in lakes, for although the Miocene boulder beds of Piedmont are more than 100 feet thick they contain no organic remains, and we know that this is a feature of modern glacial lakes. The beds rest also on Lower Miocene strata, mostly of fresh-water origin. To adduce such isolated facts as proofs of the existence of Glacial periods in Early Tertial times is as logical as it would be to argue that there is now a Glacial period in the tropics because there are glaciers there. It is as if a traveller on the coast of western tropical America, coming in sight of one of the snow-capped summits of the Andes, should contend—although the sea and the land teemed with tropical forms of life—that he was in the arctic regions. Probably throughout geological history there never was a time when some mountain summits did not rise above the limits of perpetual snow, and we may expect to find in every geological formation some ice-borne boulders, without being forced to conclude that it required a Glacial period to transport them. The only safe guides to follow are the fauna and flora preserved in the strata, and even these fail us when we go far back in geological time, for we know not what to call tropical and what temperate forms; but so far as Tertiary rocks are concerned we may accept their evidence, and they prove that there were no oscillations between extreme heat and extreme cold, but a gradual and continuous decrease of temperature from the Eocene up to the Glacial period.

Coming to the Glacial period itself, what evidence have we of the intercalation of that time of "perpetual summer" that is, according to Mr. Croll, a necessary consequence of his theory? The fact most commonly appealed to, both on the Continent and in England, in support of this supposition, is the presence of seams of lignite in Switzerland—as at Dürnten, in the canton of Zurich—resting on a great thickness of boulder clay, and capped by beds of gravel with large erratic blocks. These seams of lignite generally vary from 2 to 5 feet in thickness, but in some parts swell out to as much as 12 feet. I admit that the evidence is conclusive that after the ice—during the great extension of the Swiss

glaciers—had occupied the ground for a long period, it retreated, and peat mosses accumulated in low swampy spots; but I dispute that there is any evidence of a warm climate. Cones of the Scotch and spruce firs, and leaves of the oak, the ash, and the yew, have been found in these deposits, and, as these are all of existing species, Prof. Heer has inferred that the climate was similar to that now experienced in Switzerland. In reality it may have been colder, for all these trees range to more northern latitudes. The bones of the large Mammalia found in the same deposits tell us nothing of the climate, or, at the most, do not throw any further light on the question than is derived from a study of the vegetable remains. All that is proved is, that towards the latter part of the glacial period the ice retreated, and after a long interval advanced again, and covered some great mosses that had accumulated during its retreat. We have had a similar event, though on a smaller scale, in historical times. M. Venetz has pointed out that before the tenth century the Swiss glaciers extended further than they now do, that then for four centuries they gradually melted back, and then again began slowly to advance, and have been ever since gradually regaining their lost territory. If this be so, they must have passed over surfaces on which vegetation grew during their retreat, and if these surfaces were again uncovered we might find leaves of existing Swiss trees in deposits between two sets of Moraine gravels, one of an earlier and one of a later date than when the trees flourished.

Mr. Croll has himself advanced, as a crucial test of his theory, that as whilst one hemisphere was being glaciated the other was enjoying an almost tropical climate, and that as these conditions alternated several times during the period of greatest eccentricity, we ought to find proofs of the existence of these warm periods intercalated with those of greatest cold. And the evidence we require is, not that firs, oaks, and yews grew in Switzerland, as they do now, on moraines, during a temporary retreat of the ice, but of species that now live much further south, having then advanced far northwards. In fact, we want evidence, such as we have seen is so abundant in the Miocene strata, of a subtropical fauna and flora having flourished in Europe in interglacial times, and nothing less is satisfactory, according to this theory. The periods of greatest heat are as necessary a result of the theory as those of greatest cold, and they ought to occur alternately.

I fully believe that if any one takes the trouble to read

this paper, in future years, they will think many of my arguments unnecessary and superfluous; but my contemporaries know what a large amount of acceptance this theory has met with amongst our leading scientific men, many of whom have adopted it as the true cause of the Glacial period. What is required, therefore, at the present time, is a thoroughly exhaustive examination of it, and to the best of my ability I shall make it. The most complete geological evidence is that of the marine shells. They have been more certainly and abundantly preserved than other organisms, and from the earliest Tertiary epoch up to the present time we have an almost continuous series illustrating the successive faunas, and in the interglacial beds they have been much studied. I shall now take the evidence that these last afford us into consideration, and that nothing may be overlooked I shall take my examples from the "Great Ice Age" of Mr. James Geikie, who is one of Mr. Croll's most ardent supporters. First of all, we may dismiss all the Scotch interglacial beds as negatively hostile to the theory, as they either contain no organisms at all, or—in a few cases—some shells of arctic types; nowhere have more southern forms been found than those existing off the present coasts. Coming to England, we have the marine shells of the west coast interglacial beds,—those found on Moel Twyfaen, at Macclesfield, and generally over South Lancashire. I have, in another place, argued that these shells are of older date than the Glacial period, and that they were pushed up out of the bed of the Irish Sea by the great glacier that filled it;* but I need not go into this argument here, as, whatever the evidence may be worth, it is again hostile, and Mr. Geikie admits that "upon the whole the fossils indicate colder conditions than now obtain in the Irish Sea."† On the eastern coast most of the shells that have been found indicate a colder climate, but at Holderness a few fragments of more southern species have been discovered. Messrs. Wood and Harmer, who have described these deposits, admit that they have been transported from some other area; and Mr. Croll has himself, with great acumen, shown how they might have been pushed up out of the German Ocean by the ice that brought over blocks of stone from Scandinavia and thrust them up on the same coast. However, whether brought by currents of water, as suggested by Messrs. Wood and

* Nature, vol. x., pp. 25 and 62.
† Great Ice Age, p. 362.

Harmer, or by ice, as suggested by Mr. Croll, these broken and fragmentary shells—mixed through other transported material evidently ice-borne—are the *débris* of beds older than those in which they are now found. The Foraminiferæ of the same deposits have been examined by Messrs. Crosskey and Robertson: they, like the shells, are much worn, and present a more arctic character, varied by the presence of one or two Tertiary forms.* Altogether it appears that the deposits have been formed by the mixing together of the shells of two or more periods; and we might just as readily infer an arctic climate from the arctic shells and Foraminiferæ as a more southern one from the few fragments of species characteristic of the coralline crag, and which were probably derived from beds of that age in the neighbourhood.

In Ireland the shells found in the drift also indicate a colder climate than the present, and in Scandinavia the only evidence of the warm periods of Mr. Croll's theory, advanced by Mr. Geikie, points in reality to the opposite conclusion; that is to say, beds in Scania, described by M. Nathorst, containing Arctic plants—amongst others *Salix Polaris*, now confined to the Arctic Circle—which indicate a climate more severe than that of Northern Norway. These and other beds so far north are valuable, as evidence that the ice did not destroy all remains of the vegetation that had flourished in the so-called "inter-glacial period," and if during that time more southern forms had ever advanced northwards we ought somewhere to find their remains.

In North America there is, again, no evidence of a warmer climate having prevailed in inter-glacial times; the marine shells and the vegetable remains all point either to more Arctic conditions or to a climate not warmer than the present.

But, even if we could bring ourselves to believe that all the remains of the southern faunas and floras had been destroyed by the ice of the Glacial period, whilst the more Arctic forms had been preserved, we ought surely to find some evidence of the warm climates to the south of the limit to which the ice extended. In Sicily are preserved abundance of memorials of the cold climate of the Glacial period, when Alpine ice filled all the lakes of North Italy, covered the plains of Piedmont and Lombardy, and cooled the waters of the Mediterranean so that it was occupied by more

* Introduction to Crag Mollusca. By S. V. Wood, Jun., and F. W. Harmer. P. 22.

northern species of mollusca, such as *Cyprina islandica* and many others. In Southern Sicily a magnificent series of shells have been preserved in rocks rising 2000 feet above the sea. Amongst the latest of these deposits, the northern forms of mollusca appear, and they are nowhere accompanied, followed, or immediately preceded by these tropical species that we ought to find if Mr. Croll's theory be true; to obtain them we must go back to Early Tertiary times, to the Miocene and Eocene periods. These alternations of climate cannot have taken place; it is not possible that all memorials of Arctic faunas and floras in the Eocene and Miocene periods, and all the remains of tropical species in the Glacial period could have been destroyed, whilst in the former case the southern forms, and in the latter the northern, were abundantly preserved. And yet, strangely enough, we are told by the advocates of this theory that it is in harmony with geological facts.

Coming down to post-glacial times, we have in the marine shells only evidence of a gradual amelioration of the climate. Some of the fresh-water beds are, however, supposed to indicate that, immediately after the Glacial period, a warmer climate prevailed than we enjoy at present. They only, however, show that it was a more Continental one, which is in accordance with other facts indicating that the British Isles were then joined to Europe by continuous land. I have published my reasons* for believing that a great river, into which flowed the waters of the Rhine, the Thames, the Seine, and many other streams, ran southwards, through what are now the Straits of Dover and the English Channel, as far as, and possibly further than, the Bay of Biscay, at a time when the level of the sea stood much lower than at present. The ice of the glacial period had then retired from the southern portion of the bed of the German Ocean, but the flow of the waters northwards was still stopped by it, or, as I now think more probable, by the great moraines left across the ocean bed by it. Mr. Godwin-Austen has, in his various classical papers on the post-tertiary beds of the British Channel, shown the great probability that the Straits of Dover did not exist until after the Glacial period, but that a neck or isthmus of land stretched across, joined England to the Continent, and divided the German Ocean from the English Channel. Now, at the height of the Glacial period, we know that the greater part of the bed of the German Ocean was filled with ice, that stretched from Scandinavia

* Nature, vol. x., p. 25.

to the coasts of Norfolk, if it did not extend further south. At this time the southern part of the German Ocean bed must have been occupied by a great fresh-water lake whose arms ran up the valleys of the Thames and other rivers. The commencement of the cutting out of the Straits of Dover was, I believe, caused by the overflow from this great lake finding an outlet across the neck of land, which was gradually worn down, and the beds of gravel mantling all the lower hills of the Thames valley were, I think, beaches formed at the successively lower levels at which the lake stood. The ice to the north was now gradually receding, and leaving great banks of moraine rubbish in the old ocean bed, to be ultimately levelled by the sea when it long afterwards returned, and which now form the Dogger and other great submarine banks. At the highest point at which the freshwater lake stood, and which marks the extreme rigour of the Glacial period, we have no organic remains, but many boulders in the beach deposits apparently transported by coast ice. Lower down, the ice had retired a little to the north; the climate was still severe, but the mammoth, the woolly rhinoceros, the musk ox, the lemming, and other animals fitted to live in an Arctic climate, left their remains in the old beaches. Still lower, we find more southern mammalia coming upon the scene, accompanied by fresh-water shells, three of which are not found so far north. I thought formerly that their presence merely intimated a lowering of the lake in autumn, or that the ice had melted so far back that it partly drained around Scotland; but, on fuller consideration, I cannot believe that the hippopotamus came up, or the *Cyrena fluminalis* permanently lived in, water chilled by the melting of Continental ice; and I have come to the conclusion that the ice must have retired so far back that it drained entirely to the north of Scotland, and that it had left a great moraine stretching across the ocean bed, where the Doggerbank now lies, that closed the flow of the southern waters northwards. The Straits of Dover, and probably another barrier much further to the west, had by this time been so far cut through that the rivers stood but little above their present levels when the hippopotamus came up them, possibly only in summer. Then, too, existed great river conditions similar to those under which *Cyrena fluminalis* now thrives in Cashmere and Africa. As some additional evidence in favour of this theory, I may add that one of the three river-shells, *Unio pictorum*, has been dredged off the mouth of the British Channel in the course of the supposed great river.

On the continent of Europe, and in North and South America, no evidence whatever has been found to indicate a sub-tropical climate having prevailed in post-glacial times in the temperate regions of the globe, and I cannot but consider that the issue that Mr. Croll has based on the existence of warm climates having existed about the same time as, and intercalated between, his cold climates, must be given against him. If so, it is fatal to his theory, for he has not one whit exaggerated the importance of the necessity of these oscillations of temperature. If the theory be true, each hemisphere enjoyed the extremes of heat and cold. Just as much as the Glacial period lowered the temperature of any place below what it is now, so must the warm period that came on in about ten thousand years have raised it, and it is a rigorous deduction from the theory that, either in the southern or the northern hemisphere, or both, there must have intervened a great period of warmth as great as that of the Miocene epoch since the countries were glaciated.

There are some other facts to be accounted for that are not, I think, explained by Mr. Croll's theory, but they will be better understood if I take them into consideration under the next theory to be discusssd.

3. *Theory of a Change in the Obliquity of the Ecliptic.*—So long ago as 1688, Dr. Robert Hooke drew attention to the evidences of tropical climates having prevailed in Europe, and speculated on changes in the axis of the earth's rotation, or a shifting of the earth's centre of gravity, or a change in the obliquity of the ecliptic. The last theory was a favourite one amongst the older English geologists, but even in these early days received little favour from astronomers, for Newton pronounced against it and declared that astronomy did not countenance the theory that there had been any change in the direction of the earth's axis. The celebrated Laplace investigated the problem of the effect of the attraction of the sun, the moon, and the planets upon the equatorial protuberance, and came to the conclusion that this could only cause a variation in the obliquity to the amount of 1° 21′. More recently, Leverrier has examined the same question, and has arrived at the result that it might vary to the amount of 4° 52′, but not more. The difference between Laplace and Leverrier is a large one, but most geologists have accepted their verdict as decisive, that former great changes of climate could not have been caused by variations in the obliquity of the ecliptic.

But granted that the great geometricians could not have erred very much in their calculations, we may still, without presumption, enquire whether there are not other elements of disturbance besides those they investigated. They assumed in their examination of the problem that the thickening of matter around the equator was a constant quantity, whereas there are evidences of great upheaval and depression in remote ages that may have altered the conditions of the question. The gradual heaping up of ice around the poles in the Glacial period must have in some measure diminished the difference between the polar and the equatorial diameters. Many physicists believe that even now an elevation of land around the poles and a depression of land in the tropics is taking place.

The protuberance around the equator is not a regular one, but the equatorial circumference approaches in general outline to an ellipse, of which the greater diameter is two miles longer than the other. At the time the above-mentioned calculations were made the data did not exist for determining the irregularity. To the non-astronomical mind it appears evident that this great difference in the equatorial diameters is an element of great importance in the calculations, and as it was not considered we cannot admit that the problem has yet been decided. The great preponderance of land in one hemisphere, not arranged around the pole of the earth but in a mass whose centre is situated near the English Channel, must also be a disturbing element of no mean importance.

Our knowledge of the other planets teaches us that there is no limit to the obliquity of their axes. In Jupiter the axis is nearly perpendicular to its orbit, so that there is no change in the length of its day. In Saturn the obliquity is 29°, in Mars 30¼°, and in Venus it reaches the extreme amount of 75°, so that its tropics overlap considerably its arctic circle, and there are no temperate zones. The original cause of the inclination of the axis of the planets has never been demonstrated, and until this be done it may be allowable to suppose that changes may occur through the same cause.

Lieut.-Col. Drayson has approached this question in a different manner.* Leaving out altogether the consideration of the cause, he contends that a variation of the obliquity is taking place. He shows that according to the observations of the last four hundred years the obliquity of the

* The Last Glacial Epoch. Chapman and Hall.

ecliptic has decreased, and argues that the pole of the earth instead of describing a circle around the pole of the ecliptic describes a larger one around a point six degrees from that centre. It is admitted, and is indeed an established fact, that the obliquity is less than it was some centuries ago. but the generality of astronomers are agreed that this is owing to the small variation that the calculations of Laplace and Leverrier showed to be possible, and that it is simply a coincidence that the path described by the pole is that of a larger circle around a point a little distant from the pole of the ecliptic. They contend that the pole of the earth does describe a circle around the pole of the ecliptic as a centre, but that the outline of that circle is a waved one, and that during the time that observations have been made the direction of the pole has been down towards the trough of one of these waves, but that it will again rise as much above as it dips below the mean distance from the centre. It is an objection to this theory as well as to that of Lieut.-Col. Drayson, that it is assumed that the pole of the earth describes a circle, whereas amongst the heavenly bodies we have no circular movements. All the orbits are ellipses of varying eccentricity, and from analogy we should be led to expect that the pole of the earth would not describe an exact circle. That it does so is entirely theoretical, founded on calculations based on the assumption that the earth's equatorial circumference is a circle, which it is not. Lieut.-Col. Drayson has informed me that though he has assumed the curve to be that of a circle, the earlier observations cannot be sufficiently relied on, and it may be that of an ellipse or of a spiral.

Until astronomers have re-considered this question with the light of our present knowledge of the figure of the earth, geologists should not be prevented from speculating on the possibility of great changes in the obliquity of the ecliptic having caused former great variations of temperature. According to Lieut.-Col. Drayson, the obliquity of the ecliptic has been as much as $35\frac{1}{2}^{\circ}$. The effect of this was, he urges, the production of the Glacial period. He states that as the arctic circle would then reach nearly to latitude $54\frac{1}{2}^{\circ}$, there would be an accumulation of snow during the winter; which during the summer, in consequence of the great altitude of the sun, would be melted nearly to the poles, occasioning enormous floods. Now if this really would be the effect of a greater obliquity of the ecliptic, we might at once dismiss it as a possible cause of the accumulation of ice in the Glacial period, for it is evident that the

great mass of ice—some thousands of feet thick—that moved down southwards over the northern parts of America, Europe, and Asia, could not have been the production of a single winter. It is possible that this and some other geological speculations of the author have prevented many from taking a favourable view of his theory, and it is of importance to discuss what would be the real effect of a greater obliquity of the ecliptic.

We are able to approach this question provided with data derived from the effects of the present inclination of the axis of the earth to the plane of its orbit. To it is due the varying length of the day throughout the year in the temperate and arctic zones, and the consequent production of the seasons. If the axis, as in Jupiter, were perpendicular to the plane of the orbit, night and day throughout the world would be equal. Every day there would be twelve hours' light and twelve hours' darkness. Each place would have but one season, and eternal spring would reign around the arctic circle. Under such circumstances the piling up of snow, or even its production at the sea-level, would be impossible, excepting perhaps in the immediate neighbourhood of the poles, where the rays of the sun would have but little heating power from its small altitude.

Our summer and winter are therefore due to the present obliquity of the ecliptic, and so also is it that now around the poles some lands are being glaciated, for excepting for that obliquity snow and ice could not accumulate, excepting on mountain chains. The obliquity of the ecliptic does not affect the mean amount of heat received at any one point from the sun, but it causes the heat and the cold to predominate at different seasons of the year. Near the poles there are six months' night and six months' day, but the absolute amount of heat that arrives from the sun is the same as if there were twelve hours' light and twelve hours' darkness every day. The cause of perpetual ice and snow is not, as I have already shown, the cooling of the air by the melting snow in summer, nor the formation of clouds shutting off the rays of the sun. It is, I believe, in consequence of the reflection into space of many of the rays of light and heat that fall on a snow-covered surface, and any cause that tends to increase the amount of snow or to extend the snow-covered area will tend to chill the climate of such parts by occasioning more of the rays of the sun to be deflected and lost. Therefore a long hot summer and a long cold winter are more likely to favour the accumulation of perpetual snow

than a place under exactly the same conditions, where a thermometer exposed to the rays of the sun would register the same amount of heat received, but where the sun rose and set every twelve hours, so that the heat by day and the cold by night were never so excessive.

Thus, if we suppose the earth's axis to have been originally perpendicular to the plane of its orbit, so that it had twelve hours' night and twelve hours' day all over the world, and that from some cause or other the axis began to incline and the inclination gradually to increase, the seasons of the year in the temperate and arctic zones would tend to become more and more distinct. An ever-widening circle around the poles would be covered by snow during the cold winter, and lower the temperature of the summer by reflecting the rays of the sun as long as it lasted; and if the obliquity increased to a greater amount than at present, so would a greater area be brought under arctic conditions, and an approach be made to the cold of the Glacial period.

The accumulation of snow is dependent on another factor, namely, increased precipitation; and I doubt if any theory would satisfy the conditions of the case that simply increased the cold of the glaciated regions without providing for an increased evaporation outside these regions, and thus to allow greater precipitation upon them. An increase of the obliquity of the ecliptic satisfies this condition, for whilst on one hand the arctic circle would be extended, so on the other would the tropics; one part of the temperate zones, that next the poles, would have its mean temperature greatly lowered; whilst the other, that nearest the equator, would have its temperature raised and become an evaporating area. Thus, supposing Lieut.-Col. Drayson to be right in his theory, that at one time the obliquity was as much as about $35\frac{1}{2}^{\circ}$, the arctic circle would then reach to latitude $54\frac{1}{2}^{\circ}$, and the tropics to $35\frac{1}{2}^{\circ}$, reducing the temperate zones from their present width of 43° each to only 19°, one-half of the decrease being added to the arctic circle and one-half to the tropics. As soon, also, as the ice had extended so far as to shut off the warm currents of the ocean that penetrate nearly to the pole, much of the heat now spent in melting the ice of the arctic circle would be expended in evaporation, and precipitation would be proportionally increased.

Those who have followed me in this short argument will, I believe, admit that an increase of the obliquity of the ecliptic does appear to be sufficient to cause an addition to

the snow and ice piled up around the poles; and we may now inquire if the theory throws any light on other problems of the Glacial period, and is in harmony with the facts of geology. In doing this I shall contrast it with the other cosmical theory. The theory of the greater eccentricity of the orbit requires that the glacial periods of the two hemispheres should be at different times; that of the greater obliquity of the ecliptic, that they should be simultaneous. There is not much evidence available, but what little there is, is in favour of the glaciation of the two hemispheres having occurred at the same time. Thus, there exist glacial conditions at present around the poles, due primarily to the obliquity of the ecliptic, and these conditions are contemporaneous in the two hemispheres. More ice and snow is heaped up within the antarctic circle than at its antipodes, because a greater evaporating area of ocean surrounds it, whilst the arctic regions are almost circled by land that not only lessens the evaporating surface, but intercepts much of the moisture-bearing currents from the south. The snow piled up on the Himalayas, the Alps, and other high northern ranges, is just so much prevented from reaching the arctic regions. That the difference is due to lessened precipitation, and not to a difference of temperature, will be seen if we follow the isotherm of 30° around each hemisphere. We shall find it deviating but little in the southern hemisphere from the line of lat. 60°, being now a little to the north and now a little to the south of it. In the northern hemisphere the isotherm of 30° is much more irregular, sometimes running far to the south, sometimes far to the north, but the mean is again about lat. 60°, proving that if there was as much precipitation there would be as much ice and snow to the north of lat. 60° N. as there is to the south of lat. 60° S. Even now, if all the snow of northern mountain ranges was added to that existing to the north of lat. 60° N., the difference would be greatly lessened, and we should have in both hemispheres a partial Glacial period reaching nearly 30° from the poles, and produced by the present obliquity of the ecliptic. Only on one of the other planets has an accumulation of snow at the poles been proved to exist, namely, on Mars; which, with an obliquity of 30¼°, is glaciated at both poles at the same time. So that, judging from analogy, we might expect the glacial period of the two hemispheres to have been contemporaneous.

Many plants and some animals are found, in both the northern and southern temperate zones, separated by the whole width of the tropics, which they cannot now pass;

and Mr. Darwin has explained their presence by supposing that during the glacial period they were driven to the high lands of the tropics by the advancing ice, and that on its retreat they followed it north and south. A glacial period in one hemisphere only would not afford this means of migration; the plants and animals driven south by the northern ice would always have a hot zone to the south of them, which they could not pass.

Another class of evidence that favours the theory of the glacial periods of the two hemispheres having existed at the same time, is that connected with the lowering of the sea-level. Mr. Alfred Tylor, some time ago, advanced the theory that the piling up of ice in the northern hemisphere would lower the level of the ocean 600 feet. Mr. Croll has lately discussed the question,* and comes to the conclusion that, if each hemisphere was glaciated alternately, the level of the ocean would be raised, and not lowered, in the one in which the ice accumulated; by the melting of the ice of the opposite pole and the shifting of the centre of the earth's gravity towards that covered by an ice-cap. Though I cannot agree with Mr. Croll's estimate of the thickness of the ice, and think that it could not possibly have been highest at the pole, I have no doubt that a great lowering of the level of the ocean could not have arisen by the accumulation of ice at one pole, if at the same time that now existing at the other was melted off. But if the glacial periods of the two hemispheres were simultaneous, the water abstracted from the sea and frozen into ice at the two poles, and that impounded in the great lakes of Northern Europe, America, and Asia, by the blockage of the northern drainage of the continents by ice, must have lowered the level of the ocean to a great extent.

In my "Naturalist in Nicaragua" I stated that this decrease in the volume of the ocean could not have been less than 1000 feet. I was thus guarded because we had at that time no proof of the ice having descended from the north upon Northern Asia, and there was no certainty that the Polar basin had been filled with it. Since then I have myself found evidence in Siberia that the Arctic Sea was filled with ice, which was piled up so high that it overflowed the low lands as far as lat. 52° N. Calculating from this data, I find that the lowering of the sea-level—on the supposition that the ice was equal in the two hemispheres at the same time—could not have been less than 2000 feet, and may

* Geological Magazine, July and August, 1874.

have been much more. A glacial period in one hemisphere only would not produce this result, and therefore any evidence that tends to prove that the level of the ocean was greatly lowered in the glacial period is also evidence in favour of the northern and southern ice having been contemporaneous.

Over the whole world the distribution of many insular faunas and floras has been explained by the supposition that the islands were at one time joined to continents near them and to each other, in post-tertiary times. In every case that I have examined, the theory is that the last movement of the land has been one of depression. Thus the land over which the flora of Greenland reached that country from Europe is supposed to have sunk down. The lands connecting England with Ireland and the Continent, during the forest periods before and after the culmination of the glacial epoch; the land connecting Malta with Africa; that joining the Islands of the Malay Archipelago on one side to Asia, on the other to Australia; that connecting the West-Indian Islands with Venezuela and Yucatan; and that uniting Tasmania with Australia,—are all supposed to have been submerged by a sinking of the land, and we have in the same areas no corresponding instances of elevation. Whilst all islands having shallow channels, however broad, separating them from each other and from not distant continents, produce evidence of having been formerly connected in post-tertiary times, on the other hand islands surrounded by deep water are distinguished by peculiar faunas. Thus Madagascar is separated from Africa by a deep sea, and its fauna is wonderfully distinct, though it still shows traces of a geologically remote connection with that continent. The Gallapagos Islands are a still stronger case, for though near together they are separated by channels of great depth, and Darwin found them tenanted by distinct species of reptiles, birds, and plants. If the channels were made dry land, by the lowering of the sea, we easily understand why islands surrounded by deep water did not lose their insular character; but on the supposition that they have been produced by movements of the land, the reason is not obvious why the depressions should have been limited to a certain depth.

All round the British and Irish coasts, and around Western Europe, we have submerged forests passing under the bed of the ocean. Some—as that at Cromer—are older, others newer, than the greatest development of the ice of the glacial period. To allow these forests to have grown, we have to suppose an elevation, and for their submergence

a depression, of the land,—on the theory that it was movements of the earth's crust that brought it above and sank it below the sea. Now, in various places in the south of England, we have marine deposits a little older than the forest bed of Cromer: they occur mostly between the present tide-marks,—never higher than we may suppose the tide to have reached before the Straits of Dover were cut through. Therefore, if the surface of the land has oscillated, it is remarkable that it should have returned to the same level as it stood at before the Glacial period; but such a fact is clearly in unison with the idea that it was the mobile water that had retreated and returned. These submerged forests are not confined to Europe, but are found on the coasts of America,—as in the Bay of Fundy,—betokening that their occurrence belongs to a general and not to a local cause.

Another class of phenomena, usually ascribed to a gradual sinking of the earth's crust, but which might also be produced by the return of the sea to the level it stood at before the Glacial period, is that connected with the growth of coral islands. Darwin's celebrated essay on their formation first proved that they were due to the gradual deepening of the water. Dana, closely following Darwin in his theory, estimates that this deepening of the ocean bed from which the coral islands rise has been at least 3000 feet, and that the subsidence to which he ascribes it extends round one-fourth of the earth's circumference in the Pacific, being indicated by atolls in that ocean for 6000 miles in length and 2000 in width. In the Atlantic he considers that "the Bahamas show by their form and position that they cover a submerged land of large area, stretching over 600 miles from N.W. to S.E. The long line of reefs and the Florida Keys trending away from the land of Southern Florida are evidence that the Florida region participated in the downward movement."*

Nor are these indications of either a subsidence of the land or a rise of the level of the ocean since the Glacial period yet exhausted. C. F. Hartt considers he has found proofs in Brazil that that country stood higher when it was glaciated than it now does.† Dana has argued the same respecting the high latitudes of North America. There is hardly a mountain chain of the world that has not been supposed to have stood higher, to account for the lowering of the snow-level on its sides in the Glacial period. The Himalayas, the Alps, the Caucasus, the Pyrenees, the

* Coral Islands, 1872, p. 366.

† Geology and Physical Geography of Brazil. By C. F. Hartt. P. 573.

mountains of Syria, the Atlas Chain, the mountains of New Zealand, of California and Central America, and many others, show distinct traces of glaciers having descended either on ranges where snow now never accumulates or even falls, or else thousands of feet below the present snow-line. It has by some been considered a simple explanation of these facts, to suppose that each mountain chain was elevated a few thousand feet in the glacial period, and has since sank down. Here the land went up and here it went down, they say, and think they have found a solution, without explaining why it should or how it could have done so. I shall have some more remarks to make on this assumed elasticity of the earth's surface, but now pass on to remark how a general lowering of the sea-level would cause the snow-line to descend on every mountain chain. Mr. H. W. Bates has pointed out to me, what seems perfectly obvious when once noticed, but what had certainly not occurred to me when I first wrote on this subject, namely, that a lowering of the sea-level would produce the same effect upon the climate of any place as a rise of the land to about the same amount as the atmosphere would sink with the sea. I find that Humboldt, in whose writings are found the germs of many later theories, had made the same observation.* I fail to see how glaciers could be produced in the tropics on mountain chains far below the present snow-line in the Glacial period if it was caused by an increase in the eccentricity of the orbit; for that could not affect the mean temperature of the tropics where day and night were equal, and the heaping up of ice at one pole could not lower the sea-level much; but if it was caused by an increase of the obliquity of the ecliptic, the mean temperature of the tropics would be lowered through the path of the sun being lengthened, the snow-line would descend still farther by the lowering of the sea, and still farther from increased precipitation, owing to the greater evaporation that would take place when the shallowing of the sea shut off cold currents from the polar regions. The combination of these factors could not fail to lower the snow-line in the tropics thousands of feet, as we find it to have been lowered in the Glacial period.

The examination of the deltas of the great rivers—the Mississippi, the Ganges, the Nile, and the Po—have shown that there are land-surfaces and freshwater deposits hundreds of feet below the level of the sea. All our English rivers run in old channels now filled up nearly to low-water line, but

* Edinburgh Philosophical Journal, vol. iv., p. 267.

which are excavated in the solid rock for hundreds of feet below it. These all prove that either the land stood higher or the sea lower, and I cannot but agree with Mr. Alfred Tylor, who has ably discussed this question, that the cause is not a local one, but a general lowering of the level of the ocean all over the world in Glacial times.

To these many evidences of a rise of the level of the sea produced by the melting of the ice of the Glacial period, I think I may fairly add the traditions of mankind of one or more great deluges that overwhelmed peopled lands. In America, Africa, and Asia the remembrance of great catastrophes that nearly exterminated mankind in certain regions has been handed down, indistinctly it is true, but with a marvellous resemblance in the traditions preserved in countries of the world far removed from each other. Here, again, I think that such a general explanation as that of the rise of the waters of the ocean submerging low-lying peopled countries—accompanied by earthquake convulsions, such as were likely to be occasioned by the strains on the earth's crust when the ice melted off the mountain tops and the polar regions, and ran down to the ocean beds—is a more likely theory than that the traditions refer to local catastrophes.

We have proofs that man existed even in England before the presumed date of the return of the waters of the ocean. When the great lake that I have mentioned filled the southern part of the bed of the German Ocean, whilst the northern part was still occupied by the retreating ice, man appears on the margin of that lake when it stood about two hundred feet above the present sea-level. He follows its receding shores as the great river running from it cuts through the barriers in the English Channel, and throughout its gravelly beaches his flint implements are found along with the bones of the great mammalia. The lake is gradually lowered until the rivers running into it stand only about twenty feet above their present level, and the hippopotamus and other southern mammalia now come up the great river occasionally; then palæolithic man, and the great mammalia on which he possibly subsisted, disappear together, and the waters of the sea occupies the bed of the German Ocean and the channel of the great river. Not from such rude tribes was, however, the story of the great deluge handed down; but during the Glacial period a belt of higher civilisation seems to have girdled the world on the borders of the northern tropic, and it was probably the remnants of ruined and engulphed kingdoms of that zone from which the traditions have come down.

Mr. A. G. Renshaw has pointed out to me that the melting of the ice of the Glacial period must have occupied thousands of years, and I am quite convinced that it must have done so. The gradual growth of coral islands, and the silting up of deltas filled with fresh-water deposits, cannot be explained if we adopt the hypothesis that the ice was suddenly melted. But we do not require thousands or even hundreds of feet of submergence to overwhelm low-lying tracts of country, and I think we may fairly assume that there would be some sudden rise of the sea-level, scores of feet at least, through the rapid melting of great quantities of ice, as, for instance, when the warm ocean currents from the south first gained access to the Arctic regions, or when the immense fresh-water lakes of northern Europe and Asia, pounded back by the ice, broke through their melting barriers and ran down to the ocean. Marine deposits found alternating with land surfaces in the deltas of the Mississippi and the Po indicate such occasional more rapid advances of the sea. It may be said that I am advancing one theory—that of the lowering of the sea-level during the Glacial period—to strengthen another—that of the production of the Glacial period by an increase of the obliquity of the ecliptic ; but the lowering of the sea is more than theoretical,—it is a necessary consequence of the heaping up of ice around both poles at once, and any evidence that it was greatly lowered in Glacial times is also evidence in favour of the theory of the increase of the obliquity of the ecliptic, which would produce a Glacial period in the two hemispheres at the same time.

Whilst we have thus many indications of a general rise of the sea-level since the culmination of the Glacial period, we have a remarkable exception in a rise of land towards the north and south poles, which is believed to be still in progress. In the southern hemisphere it is certainly still in operation at intervals in the southern extremity of South America and in New Zealand. In the northern hemisphere it has been better observed on account of the greater amount of land around the polar regions. One line of elevation commences in Scandinavia at Stockholm on the eastern, and near Gothenburg on the western, coast, increasing northwards as far as the North Cape, where there are marine post-glacial deposits 600 feet above the sea. The land has been elevated since the Glacial period, for the raised beaches everywhere rest on the boulder clay with transported blocks. Professor Kjerulf, of Christiania, has shown that the highest sea-terraces contain Arctic shells, which indicate that the

movement of elevation had commenced when the waters were much colder than now.* This movement appears to be continued eastward round the Arctic sea, for, according to Wrangel, the land is slowly rising around the northern extremity of Siberia. He notices the occurrence of marine beds containing sea-shells of existing species along with the remains of the mammoth several feet above the sea-level. There is some evidence that the coasts of Scandinavia are still rising.

Another line of elevation runs north from near New York. At Brooklyn the sea-beaches with marine shells occur 100 feet above the sea. This elevation also increases northwards. At Quebec and Montreal it reaches between 400 and 500 feet, and much farther to the north within the arctic circle, on the shores of Barrow's Straits, it has carried up sea-shells of existing species to a height of 1000 feet above the ocean. The movement clearly increases towards the pole. How far it extends westward I do not know, but it decreases eastward from Montreal, and in Nova Scotia I could find no traces of any elevation having taken place.

Against these numerous instances of upheaval we have in northern regions the solitary instance of a depression of part of the coast of Greenland believed to be still in progress; and it is a very suggestive fact that that country is at present enduring intense glaciation and buried in snow and ice piled up mountains high upon it. Seeing, then, that towards both poles, with a single exception, there has been a rise of land, in some parts still going on, in all evidently accomplished since the Glacial period, it is an important enquiry whether the land so raised was above or below the level of the sea in pre-glacial times. Within the arctic circle the evidence is clear that it was not, for nowhere have Tertiary marine shells been found. Nor can it be argued that they may have existed, but have been destroyed by the ice of the Glacial period, for Tertiary land-surfaces and land-plants are abundant and well preserved. This points to the conclusion that like Greenland at present the land around the poles sank down after it was covered by ice, and has been slowly rising since it melted away. It is a legitimate speculation, and one fully warranted by the facts of the case, that the cause of the depression was the piling up of a vast weight of ice around the poles, and the cause of the elevation the removal of that vast weight by the melting of the ice. That the movement of elevation continues in some

* The Terraces of Norway. Translated from the Norsk by Dr. MARSHALL HALL.

places only shows that the earth is a rigid body and but slowly gives way to great strains. We must, according to Mr. Croll's theory, go back 200,000 years for the height of the Glacial period; but not much more than one-tenth of that time would be sufficient according to the theory of an increase in the obliquity of the ecliptic; and I submit that the shorter interval is more in accordance with the continuance of the polar movements, the facts connected with the progress of civilisation northwards, and the little change there has been in the fauna and flora of the world since the Glacial period.

If our Glacial period was merely the heaping up of ice and snow around the North Pole that now exists on both hemispheres, the result would only be a slight shifting of the centre of gravity of the earth northwards; but if it was contemporaneous in the two hemispheres, as would result from a greater obliquity of the ecliptic, the figure of the earth would be changed, its polar diameter would be lengthened, its mean equatorial diameter shortened, and a series of strains would be set up tending to restore its figure of equilibrium. And if during the Glacial period the shape of the earth had approached that of equilibrium through the sinking down of the land around the poles and the rising of land in the tropics, then, when the ice melted away, the polar diameter would be shortened, the mean equatorial diameter lengthened, and forces would be set in operation, tending to lower the land of the tropics, and raise that around the poles. Therefore I am ready to admit that some part of the deepening of tropical oceans as evidenced by the growth of coral islands and reefs—and especially any now going on—may be due to a sinking of the bed of the ocean; but in doing so I by no means admit that the whole or even the greater part of the 3000 feet or more of depression that has taken place, according to Dana, can be ascribed to that movement. But the whole of the deepening of the sea, both that arising from its surface being raised, and that by portions of its bed being depressed, has, I believe, been caused by the gradual melting of the ice of the Glacial period, liberating the water that had been piled up at the poles, and disturbing the equilibrium of the figure of the earth.

I know that eminent physicists ascribe the movements of the earth's surface to its contraction from secular cooling, and Mr. Mallet has lately ably argued that volcanoes are one of the results of the movement due to that contraction. Without wishing to call in question any theories about the

earth having once been in a state of fusion, I can find nothing to warrant the conclusion that for long geological ages it has cooled in any appreciable degree. Laplace, reasoning from astronomical observations made in the time of Hipparchus, calculated that during the last 2000 years there has been no appreciable contraction of the earth by cooling, for the length of the day has not been sensibly shortened, not even to the amount of 1-300th of a second, so that the contraction of the globe must have been inappreciably small or none at all, as it could not take place without affecting the length of the day. We may therefore ask how an amount of contraction inappreciable in 2000 years can have resulted in the great amount of movement of the earth's crust and the vast volcanic energy now apparent, or why should its tendency be to lengthen the polar and shorten the equatorial diameters ? and are not such movements more in accordance with the cause I have suggested ?

It is true that the earth must radiate heat into space; but it is not evident that it radiates more annually than it receives from the sun, and if it does not it is not a cooling globe. If earthquakes and volcanoes are the result of movements of the earth's crust—produced, not by contraction, but by the strains set in action by the melting of the ice caps of the Glacial period—so probably is what we call the internal heat of the earth increasing in depth in our mines. The usually accepted theory that the increased temperature in depth is due to a greatly heated or even fluid fused nucleus, slowly giving off its heat towards the surface, does not explain the irregular distribution of the heat. To my mind it is much more conceivable and more probable that the centre of the earth is as cold as space, and that the movements of its upper strata and the heat they give rise to are confined to a comparatively shallow envelope, say not more than 500 miles thick.

The insufficiency of the theory of central heat was strongly impressed upon me when I was studying the facts connected with the frozen soil of Northern Siberia. At Yakutsk the soil—excepting a few feet at the surface which is thawed every summer—is permanently frozen to a depth of about 400 feet. This frozen soil extends to the shores of the Arctic Sea, and in many places the cliffs bordering the rivers are composed of alternate layers of soil and ice. It is in these cliffs that the bodies of the Arctic rhinoceros and mammoth have been found with their flesh still preserved. As Lyell as remarked, since they were entombed, the soil cannot have thawed for a single season or their flesh would have

putrefied. The ice, therefore, is as old as the close of the Glacial period, at which time these great quadrupeds flourished, and at Yakutsk has remained unmelted all that time. It seems impossible that it could have done so to a depth of 400 feet from the surface if the earth was a cooling globe. If, however, the heat of the crust of the earth is due to movements within it, we can understand that in Siberia it may not have been developed to the same extent as in other parts; for, according to the researches of Murchison, that country is situated on an area of great geological stability. According to Von Cotta, it was never below the level of the ocean from the close of the Permian epoch up to the Glacial period; and I have been able to determine that this permanence of level has continued up to the present time, and that the strata of the Steppes are fresh-water deposits, excepting those round the extreme northern extremity of the country.

If, whilst accepting Mallet's ably worked out theory that volcanoes are the result of movements of the crust of the earth, I am right in ascribing these movements—not with him to the secular cooling of the globe—but to the forces tending to restore the equilibrium of the earth's figure, disturbed by the accretion of ice at the poles during the Glacial period and its subsequent liquefaction, it will add another to the many wonderful effects due directly and indirectly to the action of the sun. It was the heat of the sun that raised the water by vapourisation to the level at which it congealed near the poles; and after the earth had approached its normal form by the sinking of polar lands, it was the heat of the sun that disturbed the equilibrium again by melting the snow and ice and allowing it to flow towards the equator. Not only volcanoes but the folding of strata might be produced by these movements of elevation and depression; but I guard myself against expressing an opinion whether or not the earlier and greater geological folds and upheavals might not be due to other causes.

I have now brought forward a great variety of evidence, drawn from very different sources, that points to the probability of the Glacial periods of the two hemispheres having been contemporaneous. Of the two astronomical theories it is in favour of the one founded on a great increase in the obliquity of the ecliptic, for that would cause a heaping up of ice around the two poles at the same time. I shall now turn to the consideration of a most important class of facts only incidentally alluded to in the foregoing pages.

We have not only to account for the cold of the Glacial period, but for its converse—the heat of Early Tertiary times.

The same latitudes that in the era of greatest cold were covered with continental ice, or bore just beyond the reach of the great glaciers the stunted Polar willow and a few Arctic mosses and lichens, where the musk-ox and the Greenland lemming found their northern limit in summer, were at the commencement of the Tertiary period covered with subtropical forests. Palm-trees—of types now restricted to the Moluccas, the Phillippine islands, and Bengal,—with custard-apples, melons, and many another tropical and subtropical plant, flourished in the neighbourhood of Paris and London. Huge animals, resembling but larger than tapirs, roamed in these forests; monkies chattered amongst the trees; great tortoises crawled beneath the rank herbage; sea-snakes, crocodiles, and enormous sharks tenanted the waters. If any of the mammalia had at that time become adapted to live in an Arctic climate, they must have retired to the very Pole to find it.

It is these two extremes of heat and cold with which we have to deal. If we confine ourselves to the attempt of accounting for the cold of the Glacial period alone, we grapple with but half the problem. The climate of the Eocene period was apparently as much warmer as that of the great ice age was colder than the present. The converse of the cause of the one extreme in all probability produced the other. It has been my fortune in other branches of enquiry to find in one hemisphere the solution of a question that had puzzled me in another. For instance, the origin of large masses of gold in the gravel-beds of Australia, in districts where the auriferous lodes contained only fine grains of gold, remained doubtful until I found nearly at the antipodes of the first observation, in Nova Scotia, that the very highest parts of the lodes had in some cases been left undenuded, and that there the gold occurred in large pieces, whilst deeper only fine grains were found. The conclusion was obvious that in Australia the tops of the quartz veins containing the "nuggets" had been worn off and carried down into the valleys. And so, in studying the Glacial question, it was not until I occupied myself with the consideration of its antipodes, the climate of Early Tertiary times, that I laid hold of facts that left in my mind little doubt as to what had been the prime cause of the great oscillations of temperature.

When the subtropical fauna and flora lived in Central Europe as far as 52° N. lat., still nearer the Pole vegetation flourished similar to that which now characterises the milder portions of the temperate zones, and the representatives of

the present flora of Northern Europe lived and throve within about 11° of the Pole. Thus at Spitzbergen, far within the Arctic Circle, in lat. 78° 56′, flourished species of hazel, plane, poplar, lime, and beech trees, and Professor Heer considers that firs and poplars must at that time have reached to the North Pole if there was land there then for them to grow on.

The strata in which this fossil flora is found within the Arctic Circle are believed by geologists to be of Miocene age. This determination is based on the fact that of 137 species of plants found in the Greenland beds, 46, or one-third, are identical with species of the Miocene flora of Central Europe. This fact, however, seems to me rather to be in favour of the different age of the two deposits. It is improbable that so many species should have had such a wide range. We have seen that in the Eocene period Central Europe was occupied by a subtropical fauna and flora. Is it not likely that the time of the greatest heat in Europe was also the time of greatest heat within the Arctic Circle, and that, on the advent of the cooler climate of the Miocene, some of the species that had lived much further north migrated southwards into Central Europe, and took the place of the Eocene flora, for which the climate had then become too cool? In correlating the age of the arctic flora with that of the Miocene of Central Europe, we may be making the same mistake as future geologists would do if they assumed that the beds lying above the Cromer forest lived at the same time as some arctic ones now forming because they contain the same plants, yet the former beds were deposited at the very commencement of the Glacial period. I am not sure that the omission of the consideration of the important part that the varying climates of the Tertiary period played in causing the faunas and floras to migrate from one latitude to another may not have led to an exaggerated opinion of the great length of time occupied in forming the strata. It matters not, however, for my argument whether the arctic flora, of which we have such abundant remains, was of Miocene or Eocene age. What I have to say has nothing to do with the existence of the same species at the same time in Central Europe and in North Greenland, but with the fact that such plants were able to live at all so far north. To avoid any mistake I prefer, however, to speak of them as Early Tertiary.

In a paper on the Miocene flora of North Greenland read before the British Association in 1866, Professor Heer mentioned that more than sixty different species of plants

brought from Atanekerdluk, North Greenland, situated in lat. 70° N., had been examined by him. Amongst the trees, the most abundant is the *Sequoia Langsdorfii*, the nearest living ally of which is the *Sequoia sempervirens*, not now found farther north than lat. 53°, and which requires a mean annual temperature of at least 49° F., and that in winter the thermometer should not fall below 34° F. Cones of a magnolia have been found, proving, as Lyell has remarked, that this splendid tree not only lived, but ripened its fruit within the Arctic Circle. Vines also "twined round the forest trees, and broad-leaved ferns grew beneath their shade."* Some of the trunks of trees observed were thicker than a man's body, and one seen by Captain Inglefield stood upright as it had grown.

Nor, as we have seen, did this Early Tertiary flora end in Greenland, but is found, containing a large number of species of trees, in Spitzbergen, in lat. 78° 56′ N., or about 11° from the Pole. Prof. Heer considers that the winter temperature in Greenland could never have fallen below 34° F., and says—"These conclusions are only links in the grand chain of evidence obtained from the examination of the Miocene flora of the whole of Europe. They prove to us that we could not, by any re-arrangement of the relative positions of land and water, produce for the northern hemisphere a climate which would explain the phenomena in a satisfactory way. We must admit that we are face to face with a problem whose solution in all probability must be attempted, and we doubt not, completed by the astronomer."

Whilst there are many reasons, as I have shown in the first part of this paper, for believing that the mean temperature of England might be greatly reduced by geographical changes, there is nothing whatever to lead us to conclude that the present mean temperature of Spitzbergen could be raised by any alteration of the relative positions of the sea and the land. By the present arrangement a large body of warm water is poured past that island, deflecting the isothermal lines in a great tongue northwards, which embraces it in its apex; and no conceivable geographical re-arrangement could raise its mean temperature more above that due to its latitude than what is effected at present.

No re-distribution of land and water could compensate for the length of the Arctic night. Lyell has speculated on the possibility of the trees living without light for months, and thinks they might survive through the long darkness.

* Student's Elements of Geology, p. 223.

But long nights mean extreme cold: the one cannot occur without the other. The earth rapidly radiates its surface-heat into space, and, if the loss be not compensated for by what is received from the sun, the temperature soon falls far below the freezing-point.

Neither could any possible increase in the eccentricity of the earth's orbit alter materially the length of the Arctic night; nor could the moderate amount of change allowed by astronomers in the obliquity of the ecliptic. Taking their highest limit, the Arctic night in lat. 78° 56′ would still last for three months, during which the sun would not rise above the horizon. It is impossible but that the radiation from the earth during that time would produce intense cold. This long night could be lessened in one way, and one way only,—by a much greater change in the obliquity of the ecliptic than astronomers have yet admitted can have taken place.

In an enquiry of this kind it is well when we can get down to such a crucial fact as is that of the flourishing of many species of large trees so far within the Arctic Circle. It is of far more importance than any or all the arguments I have used about the Glacial period. It admits of but one explanation. The long Arctic nights are caused by the obliquity of the ecliptic, and only by the lessening of that obliquity can they be shortened. There is no reason to believe that this vegetation could have been fitted to endure extreme cold. It belongs to many different genera, and the greater part are not those that are now characteristic of cold regions. For these, according to Heer, we should have to go to the very Pole itself. At the same time, in North Greenland, flourished a flora that could only live where frost was unknown. Many of the same species lived much further south along with subtropical forms that prove that the climate of Central Europe was then both much warmer and more equable than it now is, and Heer considers that the mean temperature of North Greenland would have to be raised at least 29° F. to enable the Early Tertiary flora to flourish there.

I have shown that a great increase in the obliquity of the ecliptic would produce the cold of the Glacial period, let us now consider what would be the effect of a great decrease in that obliquity. Would it tend to produce conditions favourable for the growth of vegetation up to the North Pole? It will simplify the question by investigating how far an entire obliteration of the obliquity would ameliorate the climate of the Arctic regions. The present position of

the axis of Jupiter proves that there is nothing impossible in the supposition that that of the earth may also have been perpendicular to the plane of its orbit. The immediate effect would be the equalisation of night and day all over the world. With twelve hours' sunshine and twelve hours' darkness the seasons would disappear, or rather every parallel of latitude would have but one. At the equator alone would the sun rise directly overhead at noon. In the temperate zones would reign perpetual summer; within the Arctic circle perpetual spring. In Central Europe sub-tropical vegetation might then flourish. In North Greenland the sun every day would rise to a height of 20° above the horizon.

The forms of the continents were very much the same as they are now. It is probable that the Gulf Stream exercised the same sort of influence as it does at present on the climate of the North Atlantic, and it is significant of that influence that the most northern Early Tertiary forests have been found in Spitzbergen, whose shores it now laves. The flora of North Greenland suggests that a branch of the Gulf Stream also flowed up along its western coast. With twelve hours' sunshine, ice could not accumulate in Baffin's Bay, and it is not improbable that some of the warm surface currents of the ocean then found a passaget hrough Davis's Strait towards the Pole. Under such circumstances the west coast of Greenland might have its mean temperature raised as much as Prof. Heer thinks is necessary. During the day twelve hours' sunshine would give it the heat of a mild summer's day, and at night the warm currents flowing past its shores would prevent the occurrence of frost. The sequoia and the magnolia might then flourish and perfect their fruits in North Greenland; and even at Spitzbergen the Gulf Stream might cause frost to be unknown; but there the sun would rise to such a small altitude that the climate would not be warm enough excepting for hardy northern trees.

Whilst the cold of the Glacial period and the heat of the Early Tertiary period might thus be caused by a great increase or a great decrease respectively of the obliquity of the ecliptic, the extreme point to which the ice reached southwards, as in America, and that to which vegetation reached northwards, as in Spitzbergen, were both due to geographical conditions still in existence. In both periods we have evidence that the isothermal lines were deflected far northwards by the Gulf Stream, and that the east coast of America was much colder than the west coast of Europe. The evidence is

overwhelming that the primary causes of these great oscillations of temperature were changes in the direction of the earth's axis; and, fortified by the conditions that we see obtain in the other planets, we may ask astronomers to reconsider the question of the possibility of these changes having taken place. Additional data respecting the exact figure of the earth have accumulated since the problem was last treated. The irregular figure of the earth must affect the result; and it is not probable that the effect of the attraction of the sun and the planets upon an irregular equatorial protuberance can cause a perfectly circular movement of the poles. None of the other movements of the heavenly bodies are circular, and why should this one be? The weak point in Lieut.-Col. Drayson's theory is the assumption that the imaginary line that the pole of the earth traces in the heavens is that of a circle. Through removing the centre of that circle from the point first fixed by other astronomers to another, he accounts for the cold of the Glacial period, but offers no explanation of the heat of the Early Tertiary period. He has, however, informed me that the curve really traced may be that of an ellipse or of a spiral, the time over which accurate observations have been made not being long enough to determine the exact figure. Geology teaches us that the obliquity of the ecliptic has been much greater and much less than it is now, but with the cause of these changes it cannot deal. This must be left to astronomy to decide, and I doubt not that the solution of the question will be attempted, and, notwithstanding its difficulty and intricacy, accomplished.

I have now come to the end of my argument. I have had more than one object in view. Besides trying to make plain what I considered the fundamental cause of the great oscillations of temperature, of which we have such abundant proofs in geology, I desired also to indicate the vast scope of the enquiry that the study of the Glacial period involved. It is not simply a question of scratched blocks and transported boulders. The whole physical geography of the world has been affected by it. Man's early history and his present distribution are intimately connected with it. Not only the valleys and the fiords of the north, but the great plains of Europe and Asia were produced by it. Even the existence of our continents may be due to a succession of Glacial periods that have from the earliest geological times disturbed the equilibrium of the earth's figure, and the volcanoes and the earthquake shocks of the present day may be

occasioned by the slow recovery from the last disturbance of that equilibrium. Viewed in these lights, the history of the Glacial period has yet to be written; and whoever has time and ability to take up the study will find it one of extreme interest.

In treating the subject as I have done I know I must with many have weakened my argument by introducing questions not directly bearing on it. They will turn to some text-book and find it stated that the greater part of England was submerged 2000 feet below the sea in Glacial times; or that the secular cooling of the earth is an incontestable physical necessity; or that in some other way I have propounded a scientific heresy. They will fail to see that the main argument is not affected by these auxiliary theories, and they will decide against me. The human mind falls back on precedent and authority, and an original investigator must expect that every step he takes will be disputed. And in many ways the result is most beneficial, for the theories that survive do so because they have an innate vitality that carries them through all opposition; and those that cannot stand the test soon succumb to the chilling blasts of gusty criticism.

There are others, however, who will consider the argument strengthened and not weakened by these subsidiary speculations, for they know that it is characteristic of a true theory, like that of gravitation or the undulatory theory of light, that it explains numerous facts not originally contemplated when it was first suggested. Many must have been led to adopt the beautiful theory of the origin of species by natural selection, through finding that it afforded welcome help in the solution of problems in natural history besides those that Darwin first sought to explain by it. And I claim for this theory that it shows these signs of truthfulness. It not only explains the grand facts of glaciation and of the Arctic Tertiary flora, but it throws unexpected light on such far removed and seemingly unconnected facts as the traditions of a great deluge, the production of volcanic eruptions, and the growth of coral islands. It is the problem of human knowledge to bring the accumulating facts of the world's history through all time into one consistent and harmonious chain of consequences, and I trust I may in this paper have contributed towards that end.